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Tailer

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[54] **THERMAL LAG MACHINE**

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[51] **Int. Cl.**[6] **F01B 29/08**

[52] **U.S. Cl.** **60/516**; 60/682

[58] **Field of Search** 60/516, 650, 682

[56] **References Cited**

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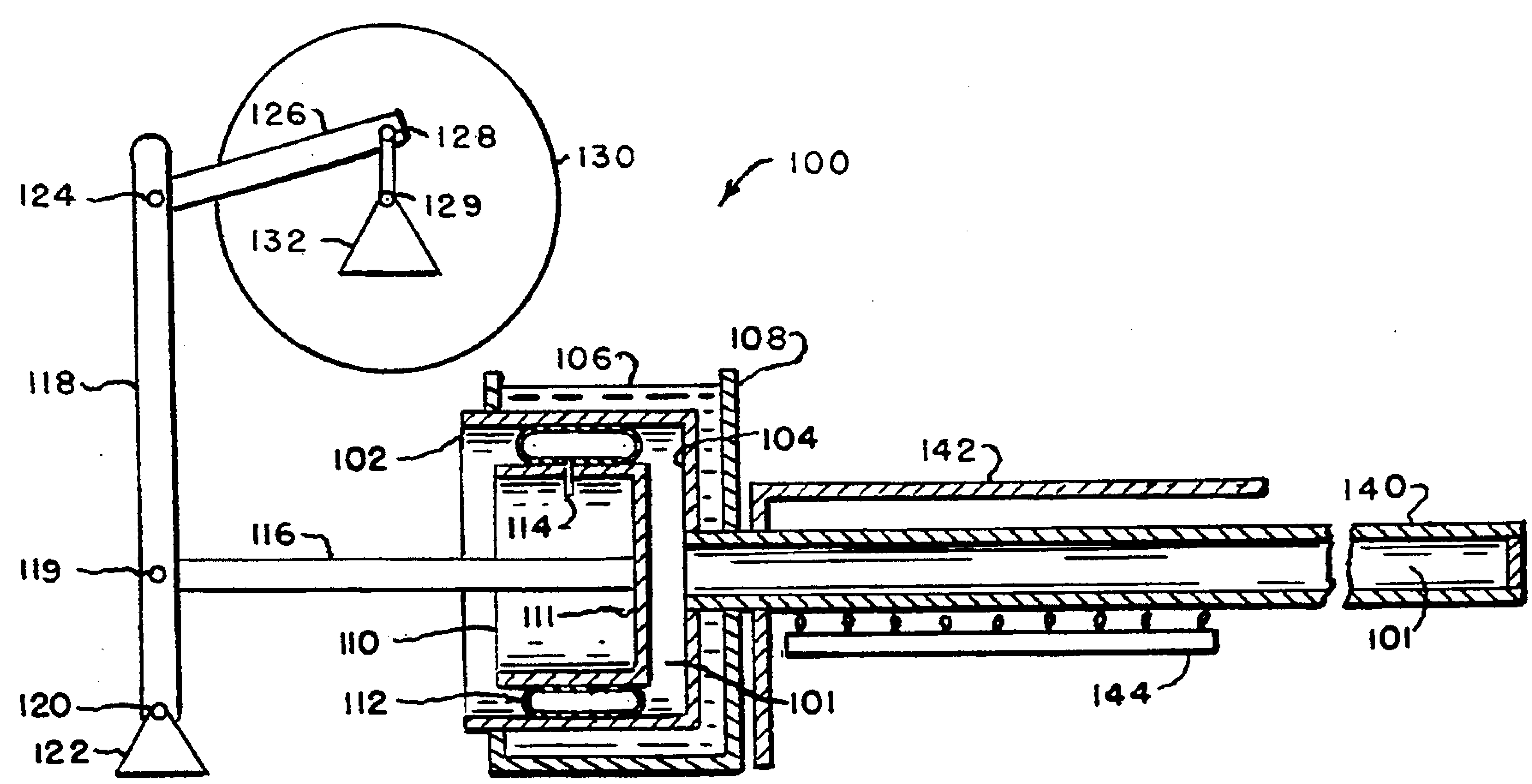
Primary Examiner—Stephen F. Husar

[57] **ABSTRACT**

A thermal lag engine has a cooled cylinder and piston connected to a heated chamber. A working fluid in the cooled cylinder and heated chamber is alternately compressed and expanded by the piston. Since there is a thermal lag or time interval before the working fluid entering the hot chamber is heated and the working fluid expanding back into the cooled cylinder is cooled, the working fluid is at a lower average temperature and pressure during compression and a higher average temperature and pressure during expansion to provide net work.

17 Claims, 2 Drawing Sheets



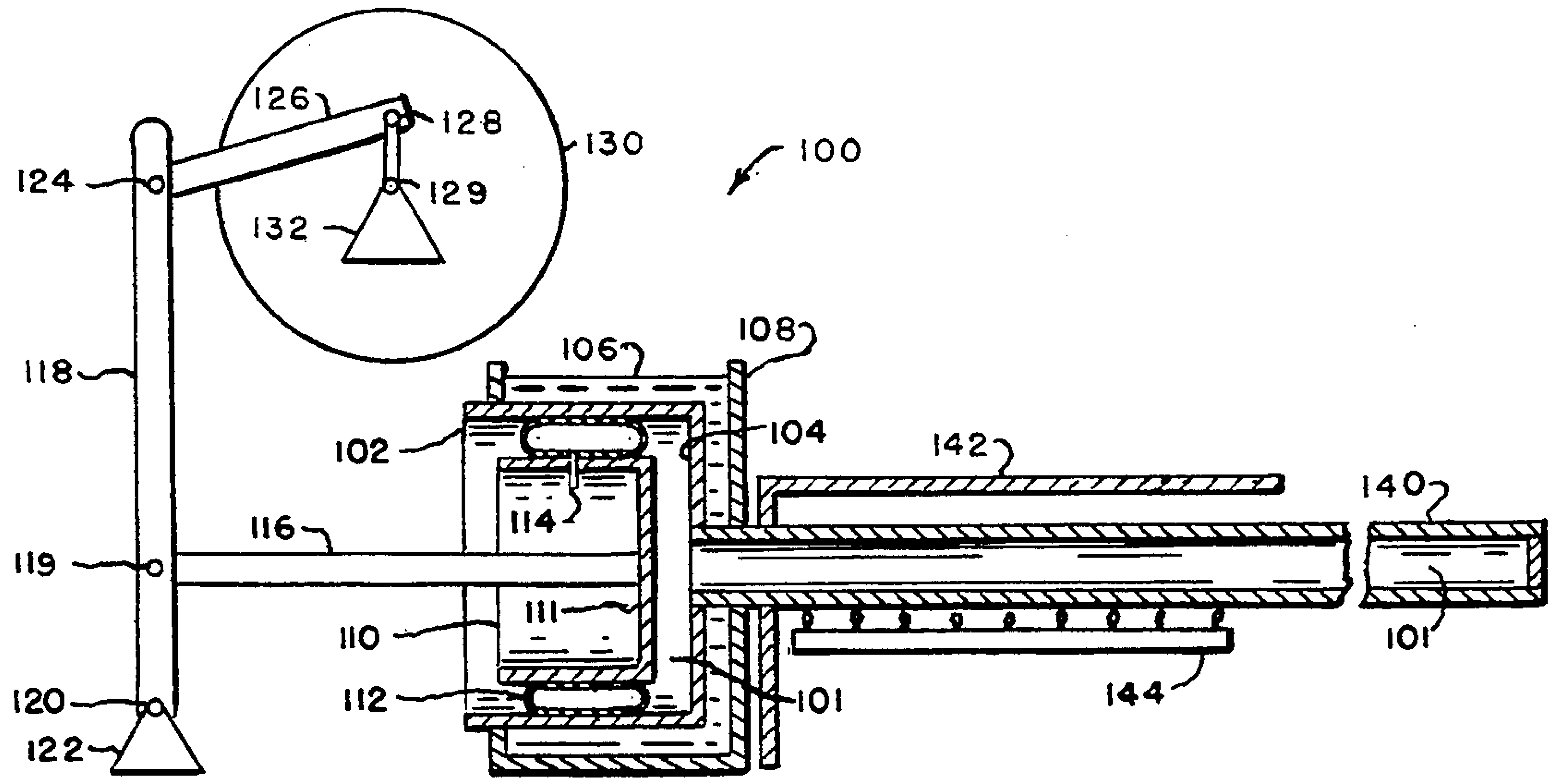


FIG. 1

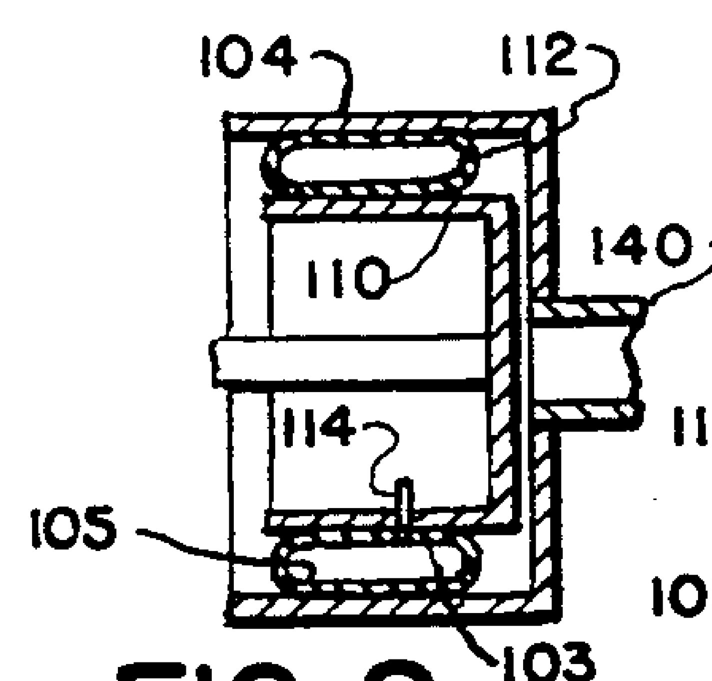


FIG. 2

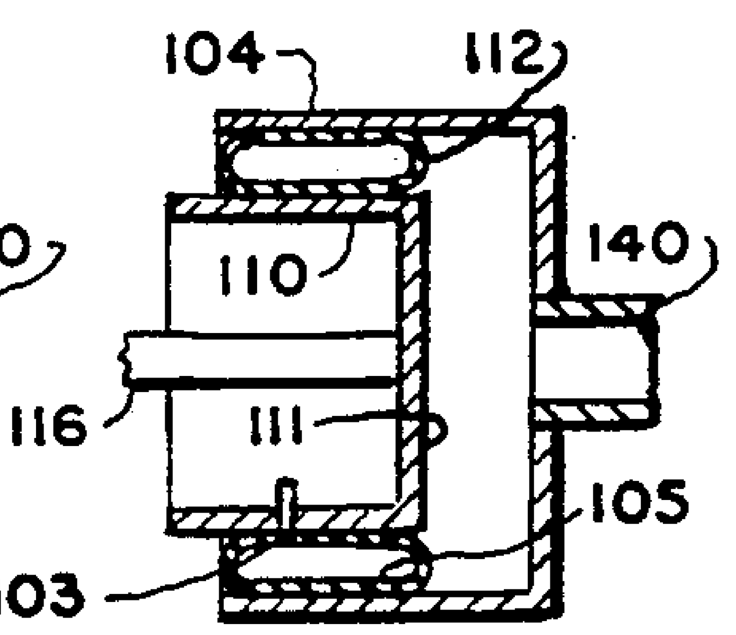


FIG. 3

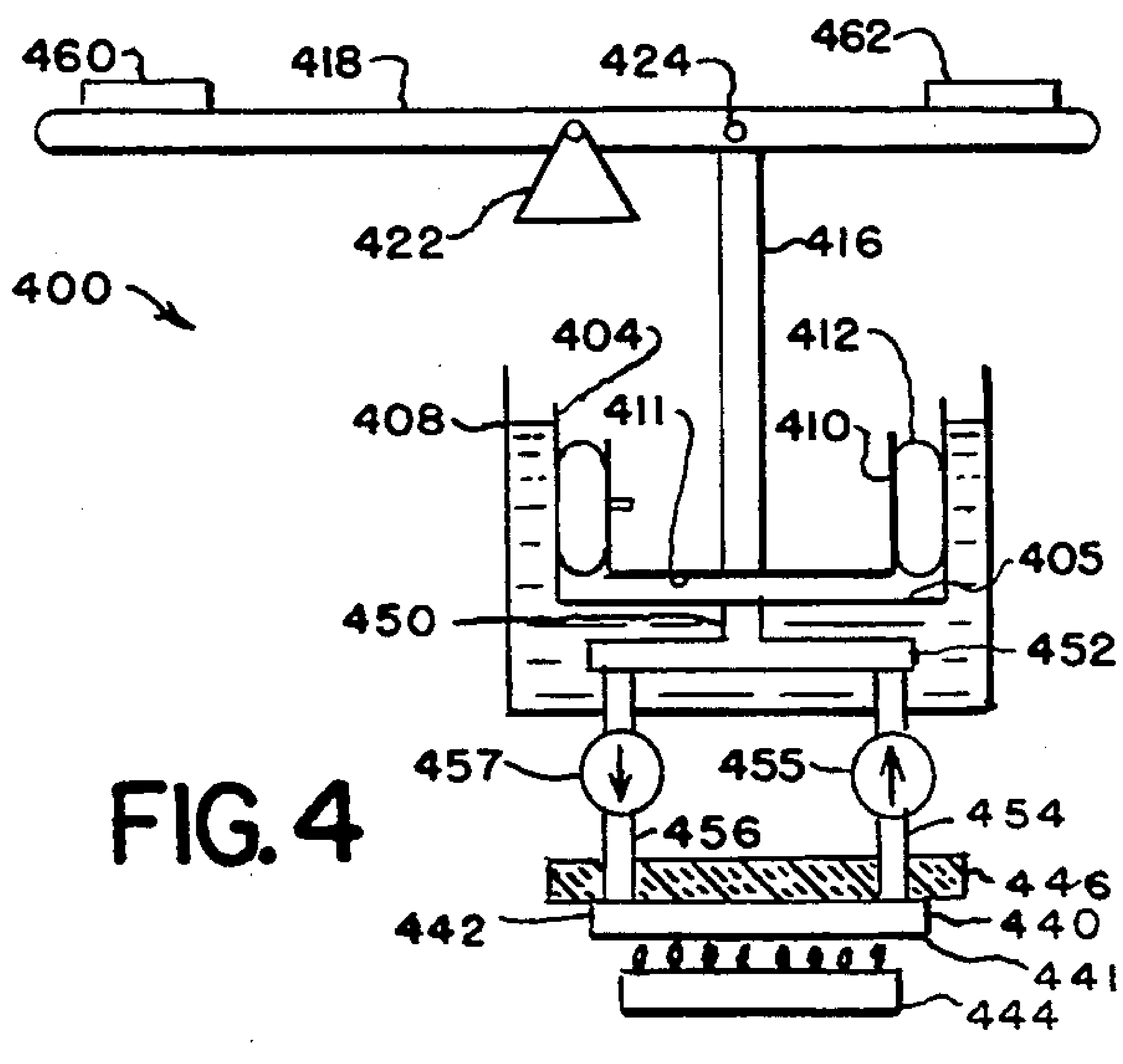


FIG. 4

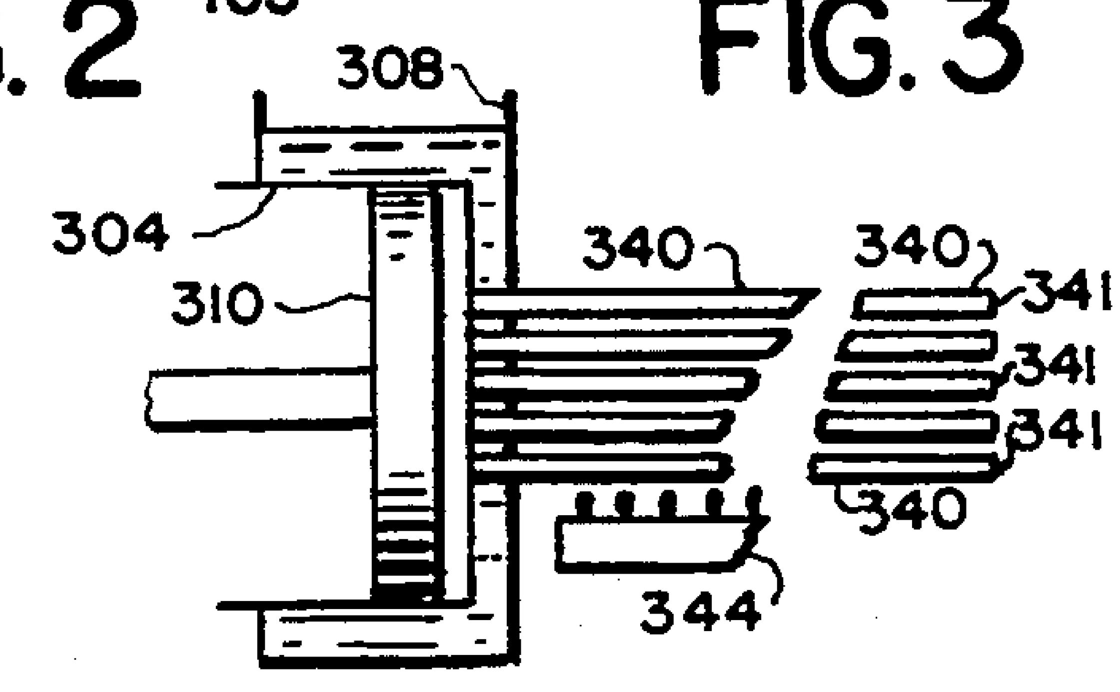


FIG. 7

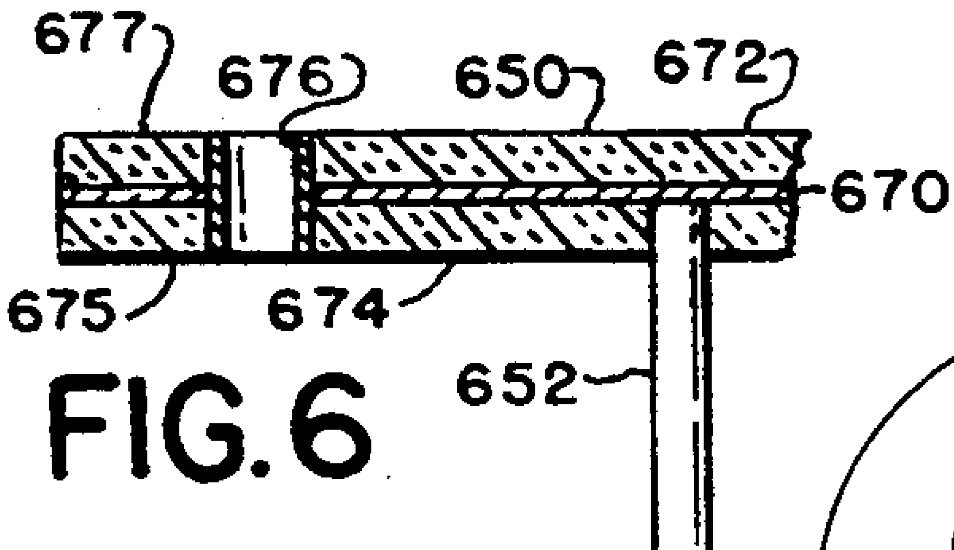


FIG. 6

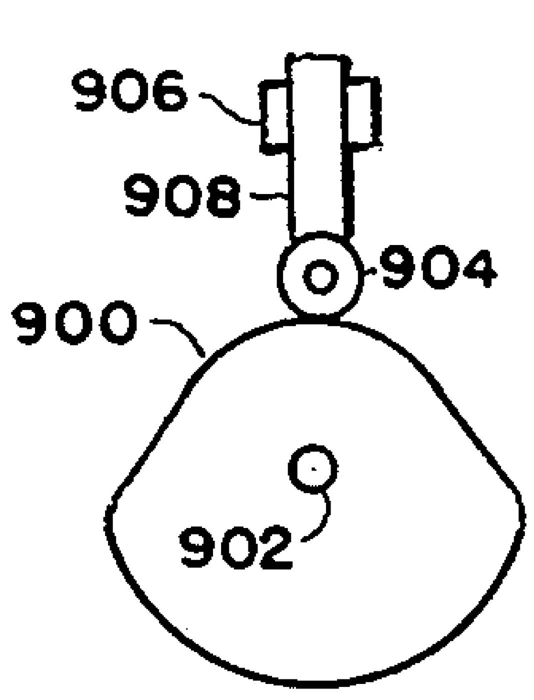


FIG. 13

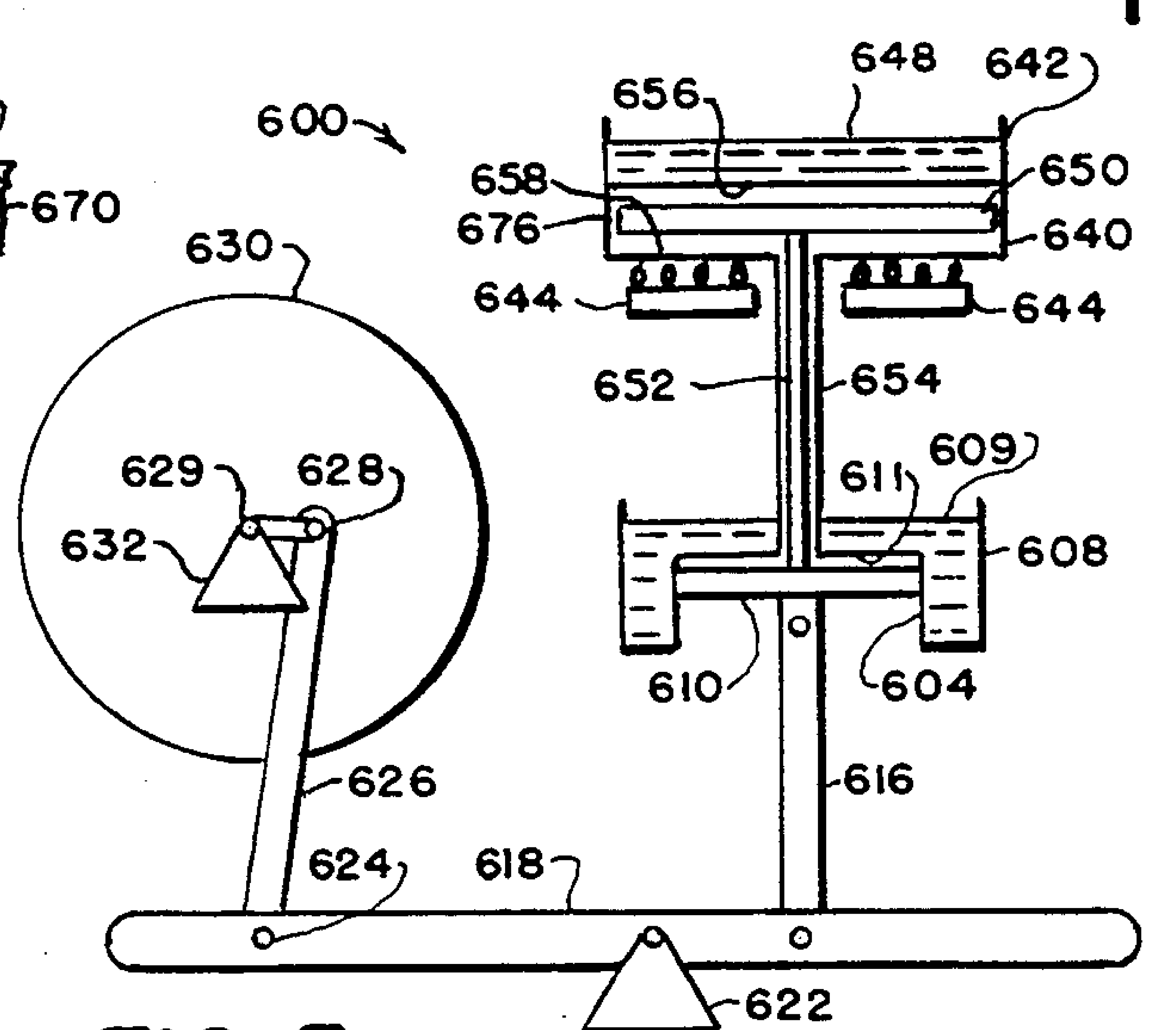
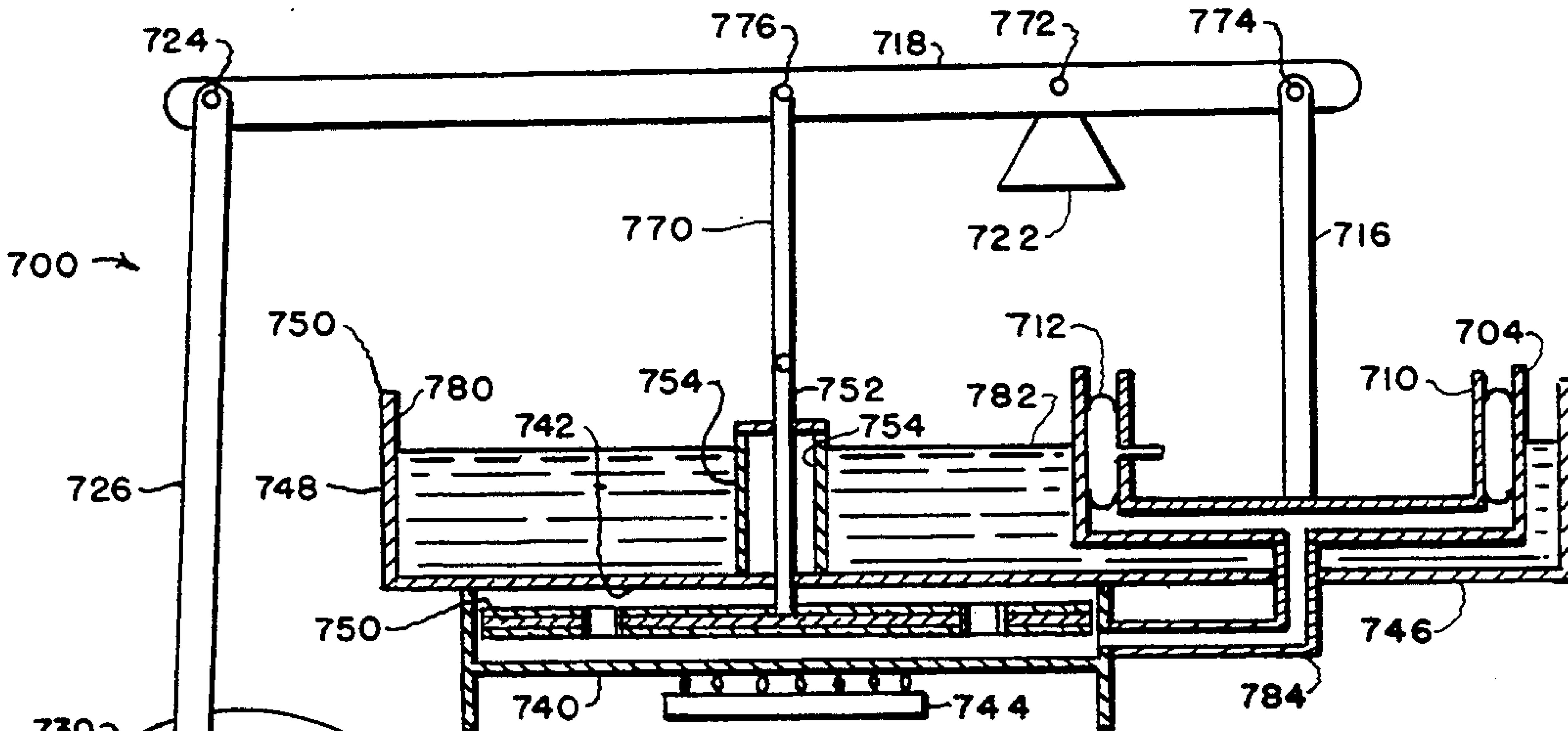


FIG. 5



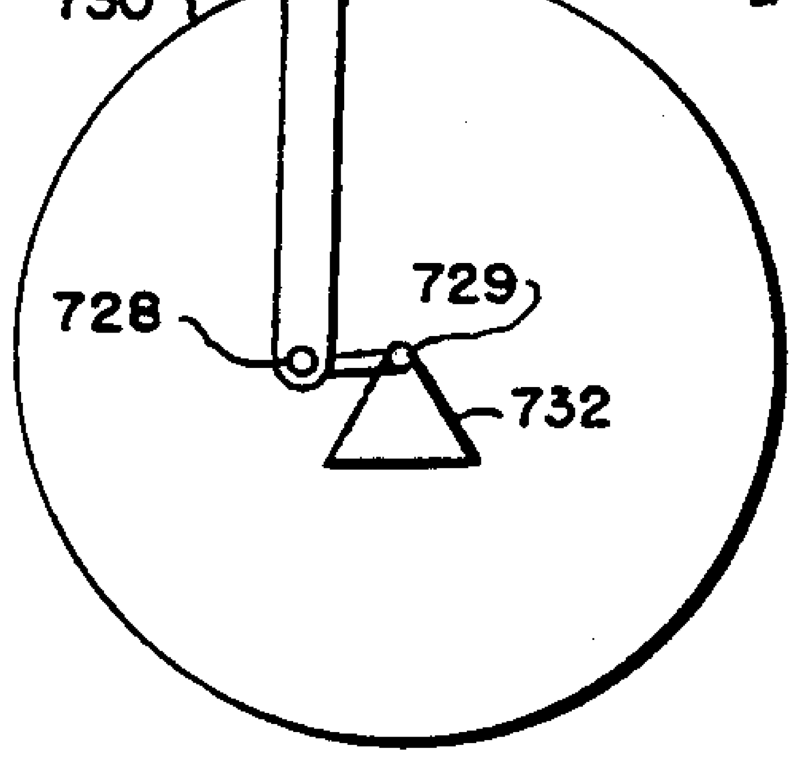


FIG. 9

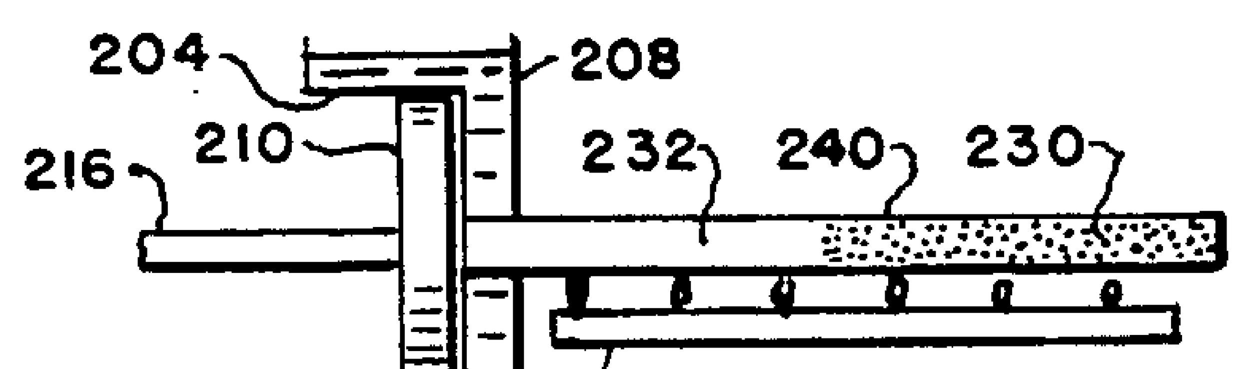


FIG. 8A

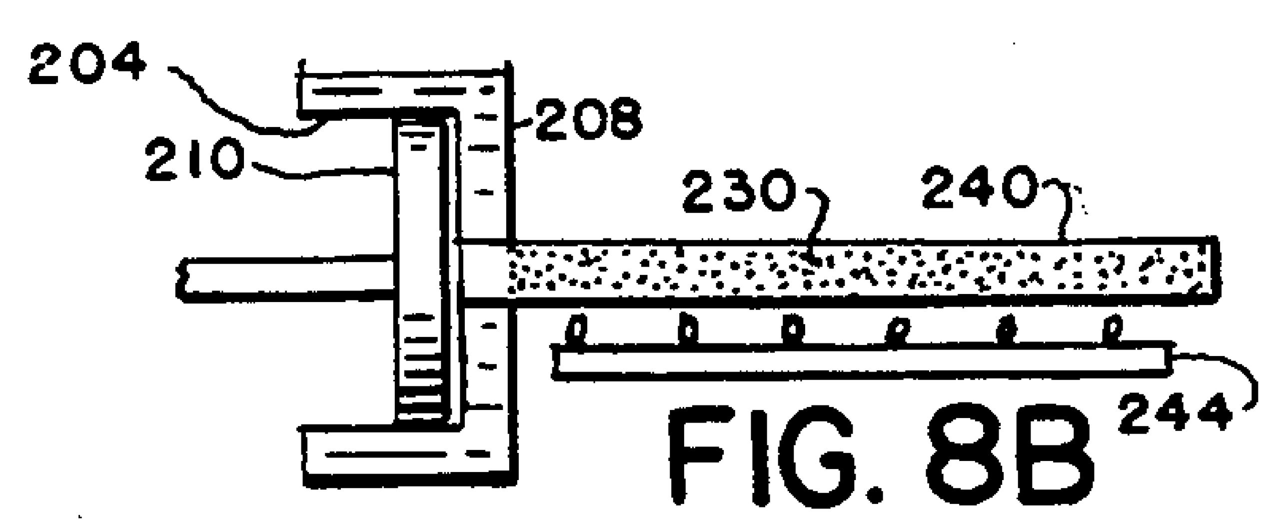


FIG. 8B

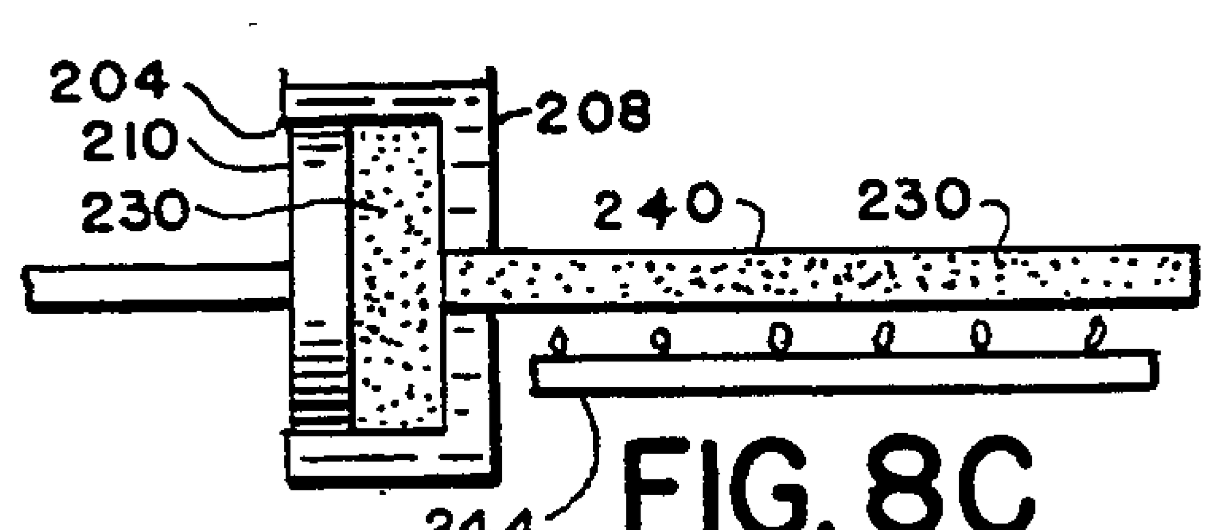


FIG. 8C

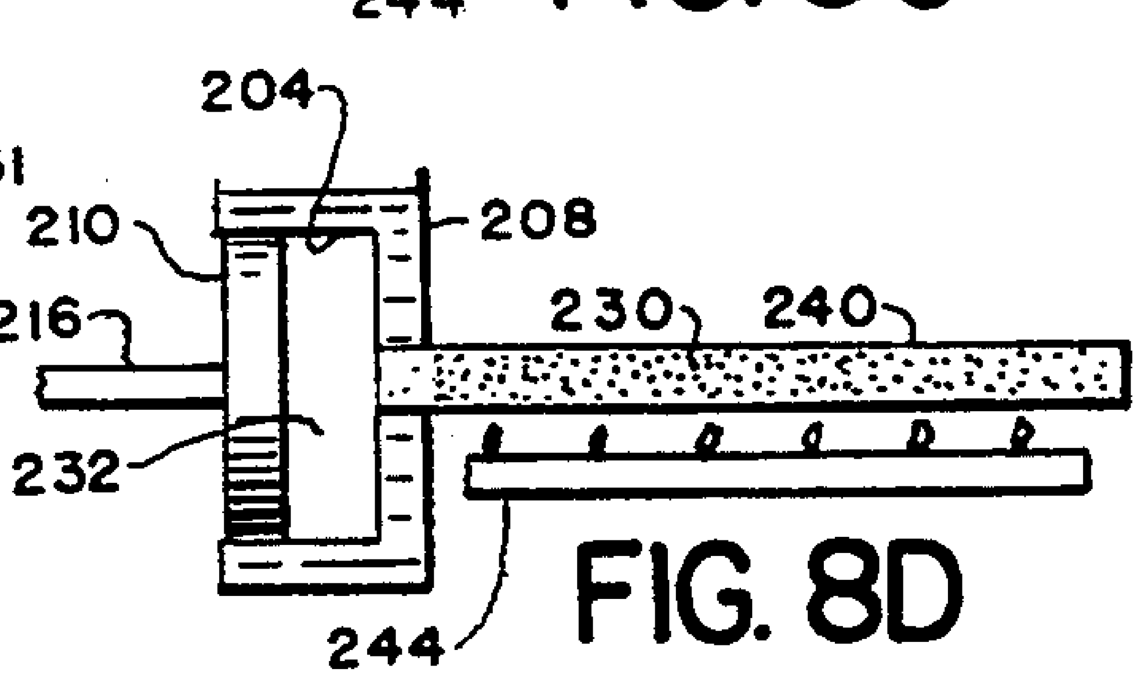
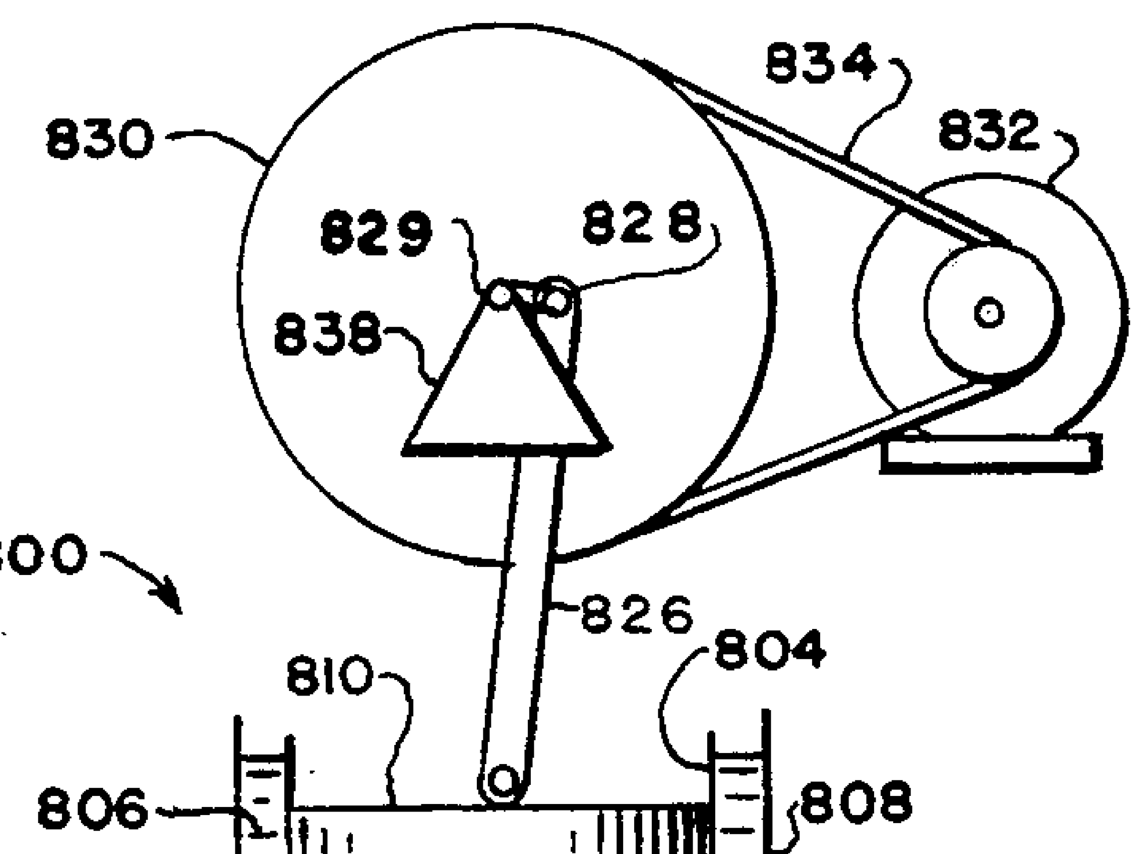
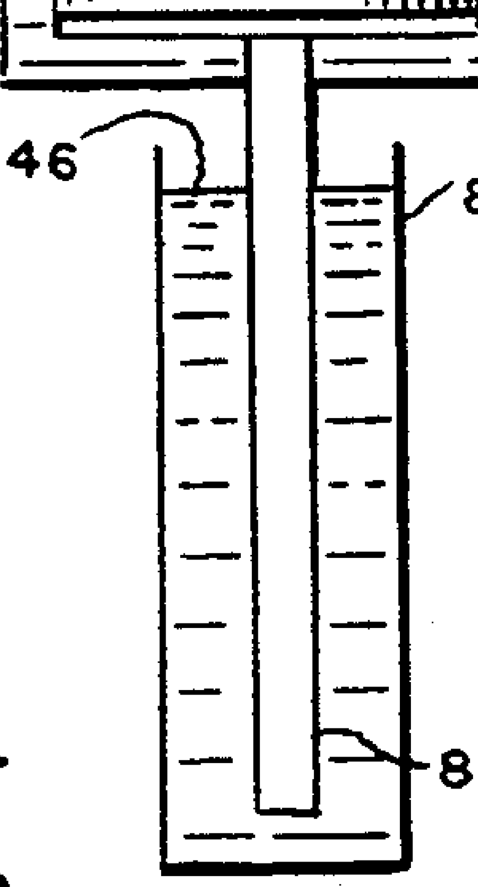
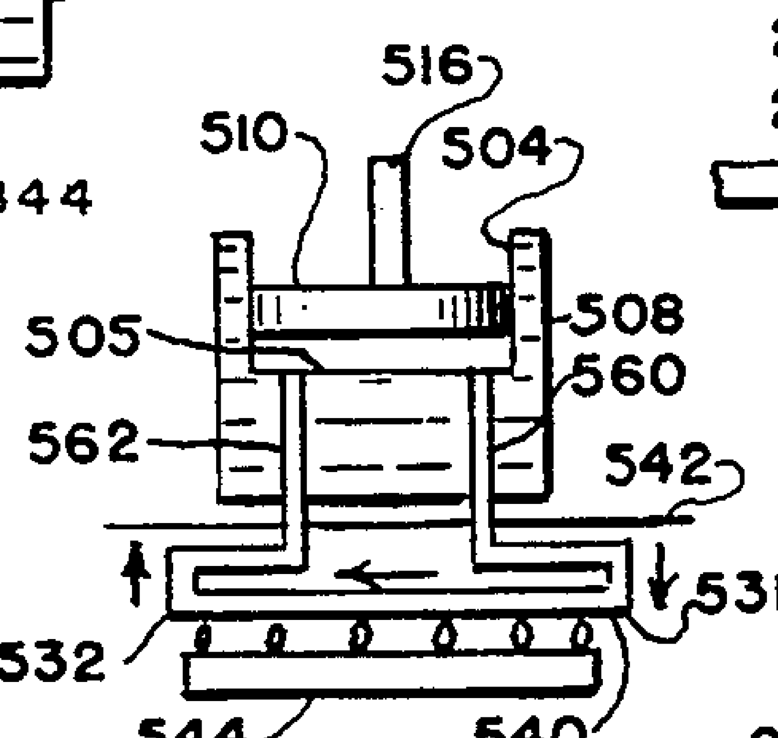


FIG. 8D







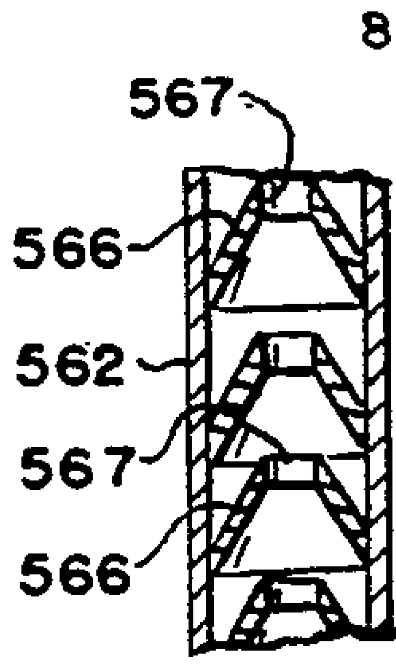


FIG. 12

FIG. 10

FIG. 11

THERMAL LAG MACHINE

BACKGROUND

This invention relates to external combustion heat engines, heat pumps, and refrigeration devices.

Experimenting with Stirling engines using air at mean atmospheric pressure as a working fluid, it was found that a main factor limiting power for a given size of engine was the time required for heat to transfer to the working fluid. For this reason an experimental engine that was not a Stirling engine was built to take advantage of and actually use this time required for heat transfer which is referred to as thermal lag. An ultimately simple engine using only a cooled cylinder and piston connected to a heated chamber ran both as a free piston engine and as a kinematic engine.

SUMMARY

A main object of this invention is to provide an external combustion heat engine of the ultimate simplicity. This engine has the potential for very high efficiency and high power for weight and volume when built with high technology materials using working fluids at high pressures. Because this engine uses the thermal lag in heat transfer, there is no need for the complex phase shifting linkages of Stirling engines or the need for the cam activated valves of steam engines, Ericsson cycle engines, etc.

The simplest form of the heat engine of this invention has a cooled cylinder containing a piston, a heated chamber communicating with the cooled cylinder, and a working fluid in the engine volume undergoing compression and expansion by the movement of the piston in the cylinder. During an engine cycle, cooled working fluid flows into the heated chamber during compression, the cooled working fluid in the heated chamber heats during a time interval at the end of compression, heated working fluid flows from the heated chamber into the cooled cylinder during expansion, and the heated working fluid in the cooled cylinder cools during a time interval at the end of expansion. Since the working fluid pressure is lower during compression and higher during expansion, net work is produced by the piston. Substantially sinusoidal motion of the piston, either free piston or connected to a crank, provides an effective time delay at the ends of the piston stroke.

The concept of this ultimately simple heat engine was reduced to practice with an engine using air at mean atmospheric pressure as the working fluid. Unlike other heat engines, the thermal lag engine need have no mechanical elements, such as pistons, displacers, or valves, associated with its heated chamber. Only working fluid flows in and out of the heated chamber. Thus, as an external combustion engine, it can operate with high temperatures in the heated chamber limited limited only by available temperature resistant materials which need not be formed to close tolerances to accommodate pistons or the like. This allows engines of high efficiency to be built to use any fuel or heat source.

In another embodiment of the invention, added cooling area may be provided by an additional cooled volume connected between the cylinder and the heated chamber. With two passages containing check valves between spaced apart portions of the cylinder and ends of the heated chamber, one check valve allowing flow into the heated chamber and the other allowing flow out, a circulatory flow is provided through the heated chamber and, to some extent, through the cylinder. Circulatory flow ensures that the last portion of the working fluid entering the heated chamber is the last to leave it so that all portions of the working fluid spend the same amount of time in the heated chamber. If there is an additional cooled volume entered by the two passages, the check valves can also provide a circulatory flow through it.

In another embodiment of the invention, the heated chamber has a heated and a cooled wall and contains a non-regenerative displacer moving between the heated and cooled walls. The non-regenerative displacer, unlike the displacer of a Stirling engine, may be directly connected to or linked to move with the piston. This avoids the complex linkages required by Stirling engines.

A thermal lag machine may be used as a heat pump or refrigeration device by driving the piston. Many other features and advantages of this invention will be better understood from the following description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a longitudinal section through a first embodiment of this invention;

FIGS. **2** and **3** are longitudinal sections through a piston and cylinder shown, respectively, at top dead center and bottom dead center;

FIG. **4** is a schematic drawing through a second embodiment of this invention having an additional cooling volume between a heated chamber and a cylinder;

FIG. **5** is a schematic drawing of a third embodiment of this invention having a non-regenerative displacer connected to a piston;

FIG. **6** is a section through a broken away fragment of a non-regenerative displacer;

FIG. **7** is a longitudinal section showing a heated chamber formed as a multiplicity of heated tubes connected to a cylinder;

FIGS. **8A**, **8B**, **8C**, and **8D** are longitudinal sections through a cooled cylinder and a heated chamber showing the cylinder and chamber, respectively, immediately after compression, after a time interval following compression, immediately after expansion, and after a time interval following expansion;

FIG. **9** is a longitudinal section through a modification of the third embodiment of this invention having a non-regenerative displacer linked to move with a piston;

FIG. **10** is a longitudinal vertical section through a fourth embodiment of this invention with a driven piston functioning as a heat pump or refrigeration device;

FIG. **11** is a longitudinal vertical section through a fifth embodiment of this invention with substantially circulatory flow through a cylinder and heated chamber;

FIG. **12** is a longitudinal section through a tube containing inserts providing somewhat unidirectional flow therethrough: and,

FIG. **13** is a side view of a cam mechanism providing dwell periods at the ends of cam follower motion.

DESCRIPTION

As shown in FIG. **1**, a heat engine **100** has a cylinder **102** having a cylinder head **104**. The cylinder **102** is immersed in a cooling fluid **106** in cooling reservoir **108**. A piston **110** in cylinder **104** is sealed with an internally pressurized annular rolling seal **112** having an inflation valve **114**. A piston rod **116** fixed to piston head **111** extends to be pivotally connected to an intermediate portion **119** of a link **118**. Link **118** has one end **120** pivotally connected to a fixed member **122** and its other end **124** pivotally connected to the connecting rod **126**. Connecting rod **126** is rotatably secured to the crank **128** of crankshaft **129** which is rotatably mounted by a fixed member **132**. Crankshaft **129** has flywheel **130** fixed on it. A heated chamber **140** extends from cylinder head **104** through cooling reservoir **108** and a flame guard **142**. A working fluid **101** fills cylinder **102** and chamber **140**. A heat source **144** under the heated chamber **140** may be an open flame gas burner or the like.

While an internally pressurized annular rolling seal **112** is shown on piston **110** inside cylinder **102**, any equivalent piston and cylinder, bellows, or diaphragm device(not shown) may be used in the practice of this invention. The seal **112** will be described as its use led to the discovery and reduction to practice of the thermal lag engine **100**. Although described in detail, seal **112** is not a required or needed element of this invention as other seal techniques may be substituted for it. The seal **112** is particularly effective to test conceptual heat engines, such as Stirling engines, using air as the working fluid operating at a mean atmospheric pressure.

Seal **112** may be a small vehicle inner tube stretched over piston **110**, inserted in cylinder **102**, and inflated through valve **114**. As shown in FIG. **2** at top dead center, the seal **112** has rolled backward on piston **110** one half the distance piston **110** has advanced in cylinder **104**. As shown in FIG. **3**, at bottom dead center, the seal has rolled forward on piston **110** one half the distance the piston **100** has moved backward. Thus it may be seen that narrow inner and outer portions **103** and **105** are always in contact with piston **110** and cylinder **102** to provide an airtight seal **112** and allow valve **114** to project into piston **110** without leakage. Since seal **112** is of an elastomer, piston **110** and cylinder **102** may have very crude tolerances as the internal pressure in seal **112** will force it to conform to any irregularities.

Seal **112** allows piston **110** to move with very low friction. Seal **112** does not require a crosshead as it tolerates some rocking of piston **110** in cylinder **102** to accommodate the curvilinear motion of link **118**.

On finding that a slight time delay in pressure change was observable when a displacer was rapidly moved in a Stirling engine displacer cylinder (not shown), it was felt that this time delay could be harnessed or put to use. For this reason, an experimental test engine, as shown in FIG. **1**, was built. It had a cylinder **104** with a diameter of 9" and a piston **110** with a diameter of 7.5". Seal **112** was a 3.50/4.10×5 vehicle inner tube pressurized to 8 psig. Crank **128** and link **118** provided a piston stroke of 0.75". The pressure change in engine volume **101** on turning flywheel **130** was between +2.5 psig to −2.5 psig. Heated chamber **140** was a capped 40" length of nominal $1\frac{1}{4}$" pipe **100**. Gas burner **144** was applied adjacent to flame guard **142** along chamber **140**. The engine **100** showed no indications of running.

On turning out burner **144**, connecting rod **126** was removed from link **124**. The heated chamber **140** had not appreciably cooled and the piston **110** was fortunately near bottom dead center. With amazement, it was observed that link **118** vibrated and the vibration continued. On relighting burner **144**, the engine **100** ran in this manner as a free piston engine for half an hour with a piston **110** stroke of about $\frac{1}{4}$" at about 200 cycles/minute.

The thermal lag engine **100** was operating, but only barely. It could not sustain a flywheel **130** even with a reduced stroke.

Links of chain(not shown) were placed in the heated chamber **140** and in the portion extending through the reservoir **108** to increase heat transfer. The $1\frac{3}{4}$" nominal pipe heated chamber **140** held about **11** chain links per inch of length and each link had a surface area of about 1 sq in. The chain increased heat transfer surface in chamber **140** from about 4 sg in/in of length to 15 sq in/in of length. This was merely an experimental expedient and not a suggested way to increase heat transfer area.

With the added chain(not shown) engine **100** then drove flywheel **130** at 450 rpm with a $\frac{3}{4}$" stroke of piston **110**. This indicated that a thermal lag engine **100** could function and that further experimentation could lead to improved power and efficiency.

While it is inexpensive to experiment with mean atmospheric pressure engines **100** with annular rolling seals **112**, these experiments indicate superior working fluids such as helium or hydrogen under a high pressure, such as 2000 psi, the types of seals used in modern Stirling engines, and other known techniques could provide powerful external combustion engines with high efficiencies. In Stirling engines other factors being the same, engine power varies almost directly with the mean engine pressure. The same should hold true for thermal lag engines to the extent that they are analogous to Stirling engines.

Since heated chamber **140** contains no working mechanisms, unlike the hot end or expansion end of a Stirling engine, a chamber **140** could be made with low dimensional tolerances of very high temperature tolerant materials such as tungsten, thoriated tungsten fibers in carbon, nobium carbide, zirconium carbide, or ceramic materials. This would allow very high Carnot efficiency heat engines to be built as a heated chamber **144** could have a temperature exceeding 2000 degrees C.

Referring now to FIGS. **8A–8D**, a piston **210** fixed to piston rod **216** is in a cylinder **204**. The volume swept by piston **210** is shown to be the same as the volume of heated chamber **240** to provide a compression ratio of 2:1. Cylinder **204** is disposed within a cooling reservoir **208**. Heated chamber **240** has a heat source **244** beneath it. Heated working fluid **230** is indicated by dots and cooled working fluid **232** is unmarked. First to be considered will be discontinuous motion of piston **210**.

In FIG. **8A**, compression has just been completed by rapid motion of piston **210** to the right as shown to top dead center in cylinder **204**. The working fluid **230** and **232** has been compressed to half its volume in the heated chamber **240** as shown. At the instant of compression, cooled working fluid **232** expelled from cylinder **204** has not had time to be heated in chamber **240**.

As shown in FIG. **8B**, after a time interval in which piston **210** does not move or moves very slightly, all the working fluid **230** in heated chamber **240** is heated.

As shown in FIG. **8C**, after rapid movement of piston **210** to the left to bottom dead center as shown, heated working fluid **230** expands into the cylinder **204** so that, for an instant, all the working fluid **230** in the engine volume is heated.

As shown in FIG. **8D** after a time delay at bottom dead center, working fluid **232** in cylinder **204** cools.

The cycle then repeats as piston **210** rapidly compresses air moving to bottom dead center as shown in FIG. **8**A. As described, this thermal lag engine **100** is an external combustion Otto cycle device with adiabatic compression, constant volume heating, adiabatic expansion, and constant volume cooling.

Whether free piston or kinematically driven by a crank **128** as shown in FIG. **1**, piston **110** or **210** will have a substantially sinusoidal motion. This provides a time lag near top and bottom dead center. As a crank **128** moves from 45 degrees before top dead center to 45 degrees past top dead center, the piston **110** will move through less that 15% of its stroke during 90 degrees of rotation of crank **128** and flywheel **130**. The same holds for the 45 degrees before and after bottom dead center where piston **110** moves through less that 15% of its stroke while the crank rotates 90 degrees. During the 90 degree rotation of crank **128** between 45 degrees before and after top and bottom dead center, the piston **110** moves through over 70% of its stroke for rapid compression and expansion.

While sinusoidal piston **110** motion is the easiest to obtain, cams and other well known devices and mechanisms can provide a long piston delay at bottom and at dead center. As shown in FIG. **13**, a cam **900** rotating with shaft **902** has a follower **904** mounted on cam rod **908** which is constrained to move vertically by guides **906**. If a piston (not shown) was linked to rod **908**, cam **900** would provide the piston with a pause or delay at top and bottom dead center.

In a thermal lag engine with a 2:1 compression ratio, only half the working fluid **230** or **232** as shown in FIGS. **8**A and **8**D, is heated or cooled. Thus half the engine volume of engine **100** of FIG. **1** is "dead space" in which the working fluid is not heated or cooled. This reduces efficiency by 50%. However, with high temperatures, the compression ratio could be increased to reduce dead space and increase efficiency. Additionally, there are adiabatic losses as cool air being compressed is heated by the compression and hot air expanding is cooled by its expansion. With high temperatures, adiabatic losses become less relevant as is the case with conventional internal combustion engines which may contain a momentary gas temperature of over 2000 degrees C. With sinusoidal motion of piston **110**, there are further losses compared to the discontinuous motion of piston **210**. The working fluid **230** and **232** may not be completely and uniformly heated and cooled. Even with these losses, using modern materials and techniques as developed for Stirling engines, an engine **100** may be built with an efficiency better than conventional Stirling or internal combustion engines. Not only is a thermal lag engine the ultimate in simplicity, but as an external combustion engine **100** it can use any fuel or heat source.

Referring now to FIG. **7**, a piston **310** is in a cylinder **304** within a cooling reservoir **308**. Heated chamber **340** is formed as a plurality of small diameter heated tubes **341** extending from cylinder **304** over heat source **344**. If the plurality of smaller diameter heated tubes **341** provide the same engine volume as a single heated chamber **140** as shown in FIG. **1**, the heat transfer area will be considerably increased. Heated chambers (not shown) with internal fins or other well known equivalent techniques to increase heat transfer area may be used with this invention. The term heated chamber is intended to include the plurality of tubes **341** and other equivalent configurations.

Referring now to FIG. **4**, a heat engine **400** has a cylinder **404** in a cooling reservoir **408**. Cylinder **404** contains a piston **410** and an internally pressurized rolling seal **412**. A piston rod **416** fixed to piston **410** extends to link **418** and is connected thereto by a pin connection **424**. Link **418** is pivotally mounted on a fixed member **422** having weights **460** and **462** mounted on its ends. A heated chamber **440** is disposed below cylinder **404** and reservoir **408**. A passage **450** extends from cylinder **404** to a cooling chamber **452** immersed in reservoir **408**.

Cooling chamber **452** provides additional heat transfer area to cool working fluid heated in heated chamber **440**. A heat source **444** is disposed below heated chamber **440** which has insulation **446** above it. At least one tube **454** connects cooled chamber **452** and heated chamber **440**. While cooled chamber **452** adds dead space to engine **400**, it provides an expedient way to add cooling heat transfer area in an experimental engine. There are many well known methods to add heat transfer area to a piston **410** and cylinder **404**, as, for example, by provided matching corrugations (not shown) to piston face **411** and cylinder head **405**. When high technology thermal lag engines are built to operate at high pressures, heat transfer will increase with pressure and heat transfer surfaces and areas can be designed for optimum effect for given desired cyclic rates.

As is further shown in FIG. **4**, two passages **454** and **456** extend between cooled chamber **452** and heated chamber **446**. The passages **454** and **456** contain check valves **455** and **457**. The check valves **455** and **457** ensure that flow from cooled chamber **452** enters one end **442** of heated chamber **440** and flow from heated chamber **440** leaves from the other end **441**. This intermittent circulatory flow ensures that the last working fluid (not shown) entering the heated chamber **440** is the last to leave it. Thus the dwell time of working fluid in the heated chamber **440** is more uniform.

The check valves **455** and **457** should be very easily opened so as not to reduce or obstruct flow therethrough and take power from engine **400**. They need only check the relatively small pressure developed by working fluid flow. For example, check valve **455** need only check pressure developed by flow from cooled chamber **452** through passage **456** and check valve **457** into heated chamber **440**.

In a free piston thermal lag engine **400**, such as that shown in FIG. **4**, both the mass and the positioning of the weights **460** and **462** fixed on link **418** will tend to determine the frequency of operation of engine **400**. Heavier weights **460** and **462** result in a slower running engine.

Referring now to FIG. **11**, a piston **510** having a piston rod **516** is disposed in a cylinder **504** which is immersed in a cooling reservoir **508**. A heated chamber **540** is disposed below a flame guard **542** and has a heat source **544** below it. A first passage **560** extends from one side of cylinder head **505** to one end **531** of the heated chamber **544**. A passage **562** extends from the other side of cylinder head **505** to the other end **532** of heated chamber **544**.

As shown in FIG. **12**, passage **562** contains conical inserts **566** fixed therein, each insert **566** containing a central opening **567**. As shown, flow is facilitated upward in passage **562** and retarded downward. With similar cones (not shown) facing downward in passage **560**, flow is facilitated downward and retarded upward. Thus the cones **566** serve two purposes. They act to some extent as did the check valves **455** and **457** in FIG.

4 to provide a somewhat circulatory flow of working fluid with the resulting advantages as stated. The cones **566** provide increased heat transfer area and may also be installed in the heated chamber **544**.

Referring now to FIG. **5**, a thermal lag engine **600** has an inverted cylinder **604** containing a piston **610**. A reservoir **608** containing cooling fluid **609** is disposed about cylinder **604**. From cylinder head **611** a passage **654** extends to heated chamber **640** through the cooling fluid **609**. Heat sources **644** are disposed below heated chamber **640**. The upper wall **656** of chamber **640** has side walls **642** forming a reservoir containing a cooling fluid **648**. A piston rod **616** is pivotally connected between piston **610** and link **618** which is pivotally mounted by a fixed member **622**. One end **624** of link **618** is pivotally connected to connecting rod **626** which is rotatably fixed to crank **628** of crankshaft **629** which mounts flywheel **630**. Crankshaft **629** is rotatably mounted by fixed member **632**.

Within heated chamber **640** is a non-regenerative displacer **650** fixed to rod **652** which extends through passage **654** to be fixed to piston **610**. The stroke of piston **610** is the same as the distance displacer **650** may move between the bottom hot wall **658** and the top cooled wall **656** of heated chamber **640**.

Referring now to FIG. **6**, a non-regenerative displacer **650** has a central metal plate **670** fixed to rod **652**. Upper and lower layers of insulation **672** and **674** are fixed to metal plate **670**. As piston **610** moves displacer **650** up and down in the heated chamber **640**, working fluid must flow past displacer **650**. It flows through the clearance **676** between the edge of displacer **650** and heated chamber **640**. To prevent any substantial regeneration or heating and cooling of working fluid contacting displacer **650** during its flow past it, additional flow may be provided through vertical channels **676** in displacer **650**. The essence of non-regeneration is to reduce the surface area of displacer **650** contacting air flowing past it. This is exactly opposite to the function of a displacer in a Stirling engine (not shown) where fine wires or screens provide a very large heat exchange area so that the regenerator captures heat from the hot working fluid flowing through it one way to give it up on flow through it the other way. The non-regenerative displacer **650** has its lower surface **675** heated by contact with bottom wall **658** and its upper surface **677** cooled by contact with top wall **656** of chamber **640**.

Thermal lag engine **600** shown in FIG. **5** operates in the following manner. When piston **610** moves rapidly from bottom dead center to top dead center, cooled working fluid in the top of heated chamber **640** above the non-regenerative displacer **650** flowing through or around displacer **650** does not have time to become heated. With a time delay of piston **610** at top dead center and displacer **650** at an upper position, the working fluid below displacer **650** is heated by contact with bottom wall **658** of chamber **640** and the lower surface **675** of displacer **650**.

On rapid downward motion of piston **610** from top dead center to bottom dead center, heated working fluid flowing above displacer **650** does not have time to cool. With a time delay at bottom dead center and displacer **650** at a lower position, heated working fluid above displacer **650** is cooled by contact with the upper surface **656** of chamber **640** and the upper surface **677** of displacer **650**. Thus it may be seen that working fluid is cooler during compression and hotter during expansion to provide net work from shaft **629**.

While engine **600** superficially appears to resemble a Stirling engine, thermal lag allows the power piston **610** and the non-regenerative displacer **650** to operate together or with a phase angle of 0 degrees. Thus the piston **610** and displacer **650** can be joined to move as a unit to avoid the complex linkages required in Stirling engines.

Referring now to FIG. **9**, a thermal lag engine **700** has a piston **710** in a cylinder **704** sealed by a rolling seal **712**. A heated chamber **740** has a heat source **744** disposed below it. The top wall **742** of chamber **740** has a lateral extension **746**. Side walls **748** and **749** form a reservoir **750**, partially over chamber **740**, for cooling fluid **782**. Cylinder **704** is mounted in reservoir **780** and has a passage **784** extending to chamber **740**. A piston rod **716** fixed to piston **710** extends to be pivotally connected to link **718** which is pivotally mounted by a fixed member **722**.

Crankshaft **729** is rotatably mounted by fixed member **732**. Connecting rod **726** is rotatably fixed to the crank **728** of shaft **729**. A flywheel **730** is fixed on shaft **729**. The upper end **724** of connecting rod **726** is pivotally fixed to link **718**. A non-regenerative displacer **750**, similar to displacer **650** shown in FIG. **6**, is disposed in chamber **740** and has an upward extending rod **752** fixed to it. A channel **754** extends upward from the top wall **742** of chamber **740** and slidably mounts rod **752** within it. An articulated link **770** connects rod **752** to link **718**. Thus it may be seen that rotation of crank **728** moves the non-regenerative displacer **750** 180 degrees out of phase with the power piston **710**.

The placement of pivotal connection **772** of link **718** between the connections **774** and **776** can determine the relative distances of travel of piston **710** and displacer **750** to allow flexability of design of the chamber **740** and cylinder **704**. Thermal lag engine **700** operates substantially as described for thermal lag engine **600**. The advantages of these engines **600** and **700** over a Stirling engine is their greatly simplified linkages. It is to be noted that any regeneration by regenerator **650** or **750** would only serve to decrease efficiency in a thermal lag engine.

In general, if a heat engine is driven it can theoretically serve as a refrigeration device or a heat pump. Referring now to FIG. **10**, a thermal lag machine **800** has a flywheel **830** driven by a motor **832** by means of belt **834**. Flywheel **830** is fixed on crankshaft **829** which is rotatably mounted by a fixed member **838**. A connecting rod **826** is journalled on crank **828** of shaft **829**. The connecting rod **826** drives piston **810** in cylinder **804** disposed in a reservoir **808** containing a fluid **806**. A chamber **840** extends from cylinder **804** into a reservoir **844** containing a fluid **846**.

If thermal lag machine **800** is to function as a refrigerator or cooler, fluid **846** will serve as a heat sink at ambient temperature. On compression by downward motion of piston **810**, working fluid in the machine volume will be heated adiabatically by compression. On piston **810** dwelling at bottom dead center, the adiabatically heated working fluid in chamber **840** will cool losing heat to fluid **846**. On upward motion of piston **810**, working fluid entering cylinder **804** will be adiabatically cooled by its expansion. On piston **810** dwelling at top dead center, the cooled working fluid in cylinder **804** will be warmed by fluid **806** which will thereby be cooled. The cooled fluid **806** can be used for refrigeration purposes. Compression ratios higher than 2:1 may be desirable.

In a like manner, if fluid **806** in reservoir **808** is maintained at ambient temperature, fluid **846** in reservoir **844** will be warmed so that the thermal lag machine **800** may serve as a heat pump.

In piston and cylinder combinations, such as piston **110** and cylinder **102**, only the cylinder **102** is shown cooled. While a piston **110** is somewhat cooled by a cylinder **102**, well known cooling techniques can be used with pistons **110**. Seals **112** can be pressurized by a cooling fluid.

What is claimed is:

1. A heat engine operating by means of thermal lag comprising, in combination, a cooled variable volume device, a heated chamber connected to said variable volume device, and a working fluid in said variable volume device and said chamber, said variable volume device causing at least partial adiabatic compression and expansion of said working fluid, said variable volume device and said chamber having heat transfer surfaces, at least some of said heat transfer surfaces in said chamber being disposed close to said variable volume device, said variable volume device having at least a reduced rate of volume variation at the end of compression and expansion so that heat transfer from said working fluid to and from said heat transfer surfaces takes place during said reduced rate of volume variation.

2. The combination according to claim **1** wherein said variable volume device is a cylinder and a piston, said piston reciprocating within said cylinder with substantially sinusoidal motion.

3. The combination according to claim **2** with the addition of a rotatably mounted crankshaft having a crank, and a connecting rod linked to said piston and rotatably connected to said crank.

4. The combination according to claim **2** wherein said piston reciprocates as a free piston.

5. The combination according to claim **1** wherein the reduced rate of volume variation at the end of compression and expansion includes a pause in volume variation.

6. A thermal lag heat engine comprising, in combination, a cylinder, a piston within said cylinder, cooling means associated with said piston and cylinder, a heated chamber closely connected to said cylinder, a working fluid in said cylinder and said heated chamber, said cylinder, said piston, and said chamber having surfaces to transfer heat to said working fluid, driven means linked to said piston reciprocating said piston in said cylinder between top and bottom dead center so that said piston causes compression and expansion of said working fluid in said cylinder and said chamber, said driven means reciprocating said piston at least at a reduced rate approaching and leaving top and bottom dead center so that said working fluid from said cylinder entering said heated chamber during compression does not have time to become substantially heated, said working fluid in said heated chamber becoming increasing heated as said piston at a reduced rate approaches and leaves top dead center, said working fluid entering said cylinder during expansion does not have time to become substantially cooled, and said working fluid in said cylinder becoming increasing cooled as said piston at a reduced rate approaches and leaves bottom dead center, said working fluid being cooler during compression and hotter during expansion so that said piston drives said driven means.

7. The combination according to claim **6** wherein said driven means provides a substantially sinusoidal motion to said piston.

8. The combination according to claim **7** wherein said driven means allows free piston motion of said piston.

9. The combination according to claim **7** wherein said driven means is a crank and a connecting rod, said connecting rod journalled on said crank and linked to said piston.

10. The combination according to claim **6** wherein said heated chamber has a heated wall and a cooled wall, and with the addition of a substantially non-regenerative displacer in said heated chamber, and means linking said non-regenerative displacer to move with said piston between said heated and cooled walls.

11. The combination according to claim **6** with the addition of a cooled chamber disposed between said heated chamber and said cylinder.

12. The combination according to claim **6** with the addition of two spaced apart passages entering said heated chamber, and two flow directing devices associated with said passages directing flow into said heated chamber from one of said passages and out of said heated chamber into the other of said passages.

13. The combination according to claim **12** wherein said flow directing devices are check valves.

14. The combination according to claim **13** wherein said flow directing devices are inserts in said passages retarding flow in one direction more than in the other.

15. The combination according to claim **12** wherein said passages extend from spaced apart portions of said cylinder.

16. The combination according to claim **2** with the addition of a cooled volume between said cylinder and said heated volume, a third passage from said cylinder to said cooled volume, said two spaced apart passages extending between said heated volume and said cooled chamber.

17. The combination according to claim **6** wherein said heated chamber comprises a plurality of smaller diameter tubes.

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